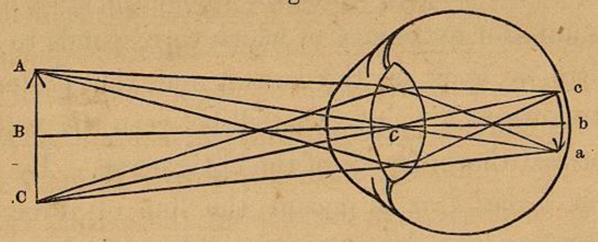
distinct inverted image of it will be formed upon the retina at *a b c*. Let *B b* be the axial ray

Fig. 7.



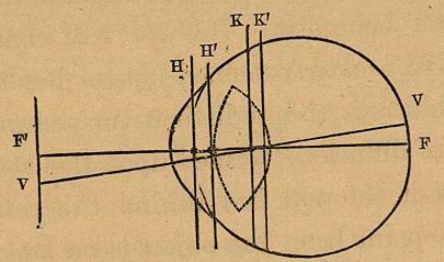
passing through the nodal point (*c*) to the retina. Through this nodal point draw a straight line from *A* to *a*. This line *A a* will be a secondary optic axis, and all the rays emanating from *A* will be united upon the retina at *a*. The straight line *C c*, passing through the nodal point, will be another secondary optic axis, and all the rays from *C* will be united upon the retina at *c*. Hence *a b c* will be the inverted diminished image of *A B C*.

Now the question, whether or not the rays from the object will be brought to a focus upon the retina, and the latter thus receive a clearly-defined image, will depend upon the situation of the object, and the distance for which the dioptric system of the eye is accommodated. The same principles as were laid down with respect to biconvex lenses apply to this case. Thus, if an eye

is adjusted for parallel rays, these will be brought to a focus upon the retina. If the object is now brought nearer to the eye, so that its rays become divergent, they will no longer be united upon the retina, but behind it. The eye will consequently not receive a clearly-defined image, but the latter will be blurred and indistinct, on account of the "circles of diffusion" formed upon the retina. As the focus of the rays lies behind the retina, each luminous point from the object is no longer represented by a point upon the retina, but by a circle (the section of each conical pencil of rays), and as these circles overlap each other, the image is rendered indistinct. These are called circles of diffusion, and take the form of the pupil, consequently their size diminishes with that of the pupil, and *vice versâ*.

For the more exact calculation of the passage of rays of light through the eye, Listing constructed a diagrammatic eye (Fig. 8) having six cardinal points, corresponding to those of optical lenses and situated on the optic axis. 1. The focus *F* (Fig. 8) situated upon the retina, in which rays falling parallel upon the cornea would be united. 2. The anterior focus *F′*, at which rays coming from the retina, and whose course is parallel in the vitreous humour, would be brought to a focus. 3. The two "principal points" H H' which lie on the optic axis in the anterior chamber

Fig. 8.



close behind the cornea (in Fig. 8 these two points lie somewhat too far from the cornea). 4. The two "nodal points" K K', in which the lines of direction cut each other, and which are situated near the posterior surface of the lens.

On account of the extremely small distance (less than $\frac{1}{4}$ of a millimètre) between the two principal points and the two nodal points, this diagrammatic eye may be simplified, and the four cardinal points be reduced to two, viz., a principal point situated in the anterior chamber, and a nodal point, situated somewhat in front of the posterior surface of the lens. The two focal points remain the same. For the method of calculating the course of the rays of light according to the cardinal points, I must refer the reader to

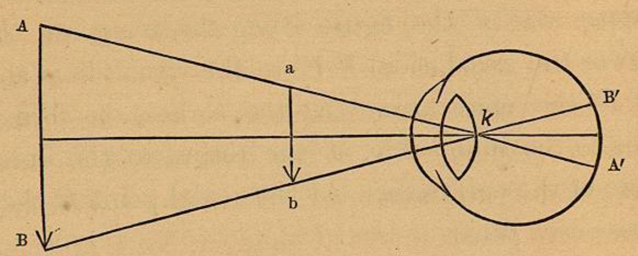
Helmholtz's Physiologische Optik, and Donders' work on the Anomalies of Refraction and Accommodation.

A glance at Fig. 8 will also explain the relative positions of the optic axis (F F') and of the visual line (V V'). The latter is an imaginary line drawn from the yellow spot to the object point. They were formerly supposed to be identical, but Helmholtz has found that this is not the case, but that in front of the eye the visual line lies inwards and generally somewhat upwards of the optic axis, its posterior (retinal) extremity consequently lying to the outer side of the optic axis and slightly below it. Thus in Fig. 8 (which represents a horizontal section of the diagrammatic eye, the upper side of the figure being the temporal, the lower the nasal side) V V' is the visual line and F F' the optic axis. At the cornea, the former lies to the inner side, at the retina, to the outer side of the optic axis. At the nodal point K they cross each other.

In the normal or emmetropic eye the visual line impinges upon the cornea slightly to the inner side of the optic axis, forming with it an angle of about 5°. But Donders has shown that in the hypermetropic eye it lies still more to the inner side, so as to form an angle of 8° or 9°; whereas, in myopia the visual line may correspond to the optic axis, or even lie to the outer side of it. These differences in the relation between the optic axis and visual line often give rise to an apparent strabismus.

The Visual Angle.—The apparent size of an object depends upon the size of its retinal image. If, for instance, the eye is adjusted for the object $A\ B$ (Fig. 9) and the lines of direction, $A\ A'$ and $B\ B'$ are drawn through the nodal point k, the angle $A\ k\ B$ will be the visual angle under which the object is seen, and this angle will equal the angle $A'\ k\ B'$. The visual angle stands in direct

Fig. 9.



relation to the size of the object, for the larger the latter is, the greater will be the visual angle, and consequently the image, and *vice versâ*. Moreover, the visual angle will also increase in size according to the proximity of the object, and diminish as the latter is further removed from the eye. If, however, the size of the object increases in due proportion with its distance, it will be seen under the same visual angle. Thus $A\ B$ (Fig. 9) and $a\ b$ are seen under the same visual angle, although the former is considerably further from the eye than $a\ b$. From this it will be easily understood, that the mere fact of a patient being able to read the smallest print does not exclude a certain degree of amblyopia. In deciding upon this point, we must always take into consideration the distance at which he can read it, and the state of refraction and accommodation.

The smallest visual angle under which an object can be distinctly seen by the eye is one of 5°. Hence, this has been taken as the standard for determining the acuteness of vision, and the test types of Snellen and Giraud-Teulon have been devised upon this principle, each type being seen under an angle of 5° at the distance in feet corresponding to its number. Thus No. 1 is seen at an angle of 5 minutes at one foot, No. 2 at 2 feet, etc.

We have now to turn our attention to the nearer consideration of the subject of refraction and accommodation.

The beginner often experiences some difficulty in realizing the difference in the meaning of the terms "refraction" and "accommodation;" and he, consequently, does not clearly comprehend the distinction between the affections of the refraction and those of the accommodation. In the former group are embraced hypermetropia, myopia, and astigmatism, for in them the refraction of the eye is altered, whilst its power of accommodation is, in pure cases, unimpaired. Amongst the affections of the accommodation we must include presbyopia, paralysis, atony, and spasm of the ciliary muscle. In presbyopia and paralysis of the ciliary muscle the power of accommodation is impaired, but the state of refraction is unaltered; whereas in spasm of the ciliary muscle the accommodation is not only affected, but the eye has also become more or less short-sighted.

By the term "accommodation" is meant the power which every normal eye possesses of adjusting itself almost imperceptibly and unconsciously for different distances. At one moment, looking at something but a few inches from the eye, at the next, regarding some far distant object, or taking in at a glance the vast expanse of miles of scenery.

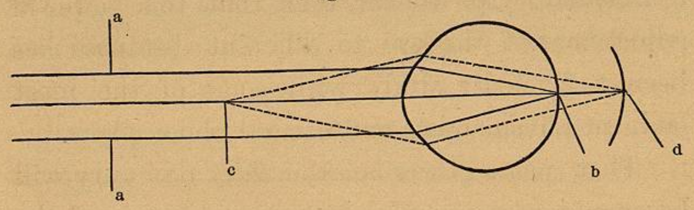
In a normal eye, the whole apparatus of accommodation is so beautifully balanced, and its functions are performed with such ease and accuracy, that, although in reality a voluntary act, its duties are from early childhood fulfilled intuitively, unconsciously. No wonder, then, that this power of adjustment of the eye to different distances has been a favourite study with some of the most eminent physiologists and natural philosophers.

That such a power is essentially necessary will become at once apparent by a consideration of the following fact, and a glance at Fig. 10.

Let us assume that the normal eye, when in a state of rest, is adjusted for objects at an infinite distance (rays from which may be considered as being parallel), *i.e.*, rays emanating from such an object are brought to a focus upon the retina without any effort of accommodation. But when the object is brought much nearer, the rays from it will become divergent, and will now no longer come to a focus upon the retina, but behind it, if the eye does not undergo some change which will increase its refraction and unite these divergent rays upon the retina.

The accompanying figure will explain this: it represents a normal eye in a state of rest, so that parallel rays (*a*), emanating from an object at an infinite distance (at or beyond 18 feet from the eye), are brought to a focus upon the retina (*b*), without any effort of the accommodation. If the object be now gradually approximated much nearer to the

Fig. 10.



eye, to *c*, say 12 inches from the eye, the rays from it will be strongly divergent, and will be brought to a focus behind the retina at *d*, if the eye does not accommodate itself for them and undergo some change in form (becoming proportionately longer), or if its power of refraction be not increased by some change in its apparatus of accommodation, so that the rays will be united upon the retina. For if this is not the case, and the rays are united *behind* the retina, circles of diffusion will be formed upon the latter, and the object appear blurred and indistinct. If the accommodation of the eye is paralysed, rays from the object *c*, 12″ in front of the eye, would be brought to a focus upon the retina by the aid of a biconvex lens of 12 inches focus, for this would render the rays parallel, and enable the eye to unite them upon the retina.

It is very necessary carefully to distinguish

between the meaning of the terms refraction and accommodation, as they signify two perfectly different things.

By refraction is understood the passive power which every eye possesses, when in a state of rest, —*i.e.*, adjusted for its far point—of bringing certain rays to a focus upon the retina without any active effort or participation of the muscular apparatus of accommodation. This power of refraction is due to the form of the eye and to its different refractive media.

We have just seen (Fig. 10) that the state of refraction of the normal eye is such that, when it is in a state of rest, parallel rays are brought to a focus upon the retina without any effort of the accommodation. Its furthest point of distinct vision lies at an infinite distance. Donders terms this condition "Emmetropia." He says,* "The refraction of the media of the eye at rest can be called normal in reference to the situation of the retina, only when parallel incident rays unite on the layer of rods and bulbs. Then, in fact, the limit lies precisely at the measure; then there exists emmetropia (from ἔμμετρος, modum tenens, and ὤψ, oculus). Such an eye we term emmetropic.

* Donders "On the Anomalies of Accommodation and Refraction of the Eye," p. 81. New Sydenham Society, 1864.

"This name expresses perfectly what we mean. The eye cannot be called a *normal* eye, for it may very easily be abnormal or morbid, and nevertheless it may be emmetropic. Neither is the expression *normally constructed eye* quite correct, for the structure of an emmetropic eye may, in many respects, be abnormal, and emmetropia may exist with difference of structure. Hence the word emmetropia appears alone to express with precision and accuracy the condition alluded to."

The state of refraction may deviate from the emmetropic condition in two ways.

1. The principal focus of the eye, when adjusted for its far point, lies in front of the retina (myopia).

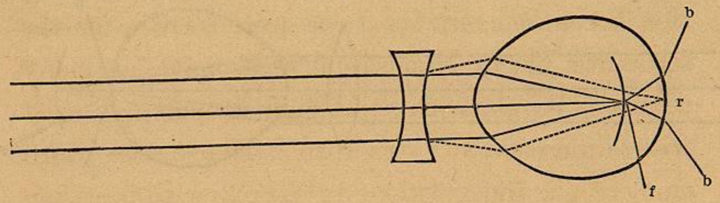
2. The principal focus lies behind the retina (hypermetropia).

In the myopic eye, parallel rays are not united upon the retina, but in front of it, when the eye is in a state of rest. The eyeball, in fact, is either too long, or the state of refraction too high, so that when the eye is adjusted for its far point only those rays which come from a finite distance, and impinge in a sufficiently divergent direction upon the eye, are united upon the retina.

Fig. 11 represents a myopic eye, in which parallel rays are brought to a focus, not upon the

retina (r), but before it (f); circles of diffusion (bb) are formed upon the retina, and the object,

Fig. 11.

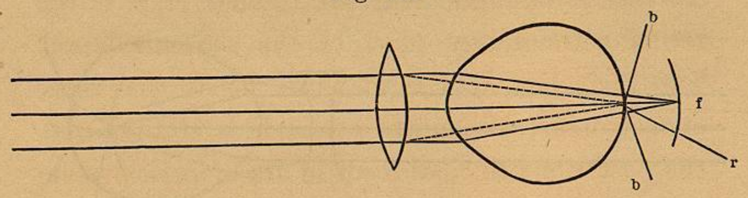


consequently, looks indistinct and blurred. In order to render the myopic eye capable of seeing distant objects (rays from which impinge in a parallel direction upon the eye), we must place that concave lens before it which will give the parallel rays such a divergent direction that they are united upon the retina.

In hypermetropia, on the other hand, the refractive power of the eye is too low, or the antero-posterior axis of the eyeball too short, so that when the eye is in a state of rest, parallel rays are not united upon the retina, but behind it, and only convergent rays are brought to a focus upon the latter.

Fig. 12 represents a hypermetropic eye, in which, either on account of its being too short in the antero-posterior axis, or its possessing too low a power of refraction, parallel rays are brought to a focus, not upon the retina (*r*), but behind it at *f*;

Fig. 12.



circles of diffusion (*bb*) are formed upon the retina, and the object appears indistinct. To remedy this, the eye undergoes a change in its accommodation, so as to increase its power of refraction sufficiently to unite parallel rays at *r*. The less the power of refraction of the hypermetropic eye, the greater must be this effort of the accommodation; and it must increase, of course, proportionately as the object is brought nearer to the eye. By placing a suitable convex lens before the eye, the parallel rays are rendered so convergent that they are united upon the retina (*r*) without any effort of the accommodation; and we thus place the hypermetropic in the same condition as the emmetropic eye, upon the retina of which parallel rays are united without any effort of the accommodation.

On comparing these three figures, the reader

will at a glance observe the difference between the emmetropic, the myopic, and the hypermetropic eye.

In the *emmetropic* eye, rays from an infinite distance are united upon the bacillar layer of the retina without any effort of the accommodation. The limit lies at the measure, hence the name emmetropia. When the eye is in a state of rest, the posterior principal focus of its dioptric system falls on the external layer of the retina.

In a state of rest, the myopic eye is not adjusted for parallel, but for more or less divergent rays, and the parallel rays are, therefore, brought to a focus *before* the retina. The posterior principal focus lies, consequently, in front of the retina; the furthest limit lies within the normal measure: the measure is too short, and hence Donders has proposed the name brachymetropia (βραχὺς, brevis, μέτρον, modus, ὤψ, oculus). He thinks it however preferable to retain the old term myopia.

The *hypermetropic* eye, when in a state of rest, is, on the contrary, adjusted for convergent rays, parallel rays being brought to a focus *behind* the retina. The posterior principal focus lies behind the bacillar layer of the retina: its limit lies *beyond* the measure, and he has therefore termed it hypermetropia (ὑπερ, super, μέτρον, modus, ὤψ, oculus).

In order to express that the eye is not emmetropic, Donders proposes the term *ametropia* (from ἄμετρος, extra modum, and ὤψ, oculus); and he observes that brachymetropia and hypermetropia are both, therefore, referrible to it. Formerly, presbyopia and myopia were supposed to be opposite conditions. This is, however, erroneous. In myopia there is an abnormal position of the far point, whereas, in presbyopia the position of the far point is normal, but that of the near point is changed, being removed further from the eye. Indeed, we may have the two conditions co-existing. Presbyopia is not, therefore, an anomaly of refraction, but a diminution in the range of accommodation.

It has long been a keenly debated question in what the changes of accommodation of the eye consist, and various opinions have been advanced. Some have thought that the cornea undergoes some alteration during accommodation for near objects, so that its power of refraction is increased, and the eye enabled to adjust itself for reading, writing, &c.; but, apart from other reasons against this theory, Helmholtz has shown, with his ophthalmometer, that there is no alteration in the curvature of the cornea during accommodation.

Others have supposed that the muscles of the eyeball play an important part in bringing about, in conjunction with the ciliary muscle, the adjustment for near objects. But that this is not the case has been incontrovertibly proved by a case of Von Graefe's, in which all the recti and obliqui muscles of both eyes were paralysed, so that the eyeballs were completely immoveable; and yet the power of accommodation was perfect.

It has at length, however, been definitely settled, chiefly by the experiments of Cramer and Helmholtz (conducted independently of each other), that the necessary change in the refraction of the eye during accommodation is due to an alteration in the form of the crystalline lens. Helmholtz found, by means of his ophthalmometer, that the lens did not change its position during accommodation for near objects, but that this was brought about by a change in the curvature of the anterior and posterior surfaces of the lens, which become more convex (the lens itself thicker from before backwards), so that the lens acquires a higher power of refraction, and consequently a less focal distance, by which means rays from even very near objects are brought to a focus upon the retina. He found, with the ophthalmometer, that the eye undergoes